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GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station

PROJECT INITIATION

Date: 6/25/73

Project Title: Dental Inlay Study

Project No.: A-1543

Project Director: Mr. H. P. Cotten

Sponsor: Dr. W. E. Swinson, Jr. (D.D.S.)

Effective: June 11, 1973 Estimated to run until: December 10, 1973

Type Agreement: Standard Industrial dated 5/28/73 Amount: $ 9,951.00

REPORTS: Monthly Letter Reports; Final Report

SPONSOR CONTACT PERSONS: Dr. W. E. Swinson, Jr.
2178-B Briarcliff Village
Shopping Center
Atlanta, Georgia 30345
PHONE: 938-7330

Assigned to: Sensor Systems Division

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GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station

PROJECT TERMINATION

Date February 5, 1974

PROJECT TITLE: "Dental Inlay Study"

PROJECT NO: A-1543

PROJECT DIRECTOR: Mr. H. P. Cotten

SPONSOR: Dr. W. E. Swinson, Jr. (D.D.S.)

TERMINATION EFFECTIVE: January 22, 1974 (Final Report submitted)

CHARGES SHOULD CLEAR ACCOUNTING BY: ASAP

CONTRACT CLOSEOUT ITEMS REMAINING: Final Statement of Account in settlement of advance payment as soon as all charges clear.

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Form EES 402 (R10-62)

A-1543

ENGINEERING EXPERIMENT STATION

GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

5 July 1973

Dr. W. E. Swinson
2178-B Briarcliff Village
Shopping Center
Atlanta, Georgia

Reference: Dental Inlay Study

Subject: Progress Report No. 1 for the period 11 June 1973 to 10 July 1973.

Dear Dr. Swinson:

Notification of contract award was received with the effective date of 11 June 1973. Project organization began immediately. The Engineering Experiment Station (EES) Project Number assigned for this program is A-1543.

A literature search is currently underway to determine what machines are commercially available that either provide direct machine control by tracing an object or can produce a tape to be used on numerical controlled equipment. Manufacturers will be called to determine such operating parameters as, minimum probe size, accuracy of tracing, size and cost of equipment, etc. These inputs will determine which types of machine might be the best suited to measure a mold. For your information, I am enclosing some copies of articles that have been found.

During the next reporting period, it is anticipated that studies into casting and molding techniques will be started. Of particular interest will be the use of the "Adaptic" molding kit used in conjunction with the model teeth that you have supplied.

During the coming months of this project, I will try to keep you informed by weekly phone calls as to progress or problem areas. If you have any questions or if I can be of service, please do not hesitate to call.

Very truly yours,

Henry P. Cotten
Project Director

dab
Enclosure

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332
10 September 1973

Dr. W. E. Swinson
2178-B Briarcliff Village Shopping Center
Atlanta, Georgia 30345

Reference: Dental Inlay Study

Subject: Progress Letter No. 3 for the period
11 August 1973 to 10 September 1973

Dear Dr. Swinson:

In trying to narrow down a suitable choice of equipment to do the machining, The Boston Digital Corporation in Ashland, Massachusetts was contacted. They are receptive to the idea of trying to machine the inlay. However, they do not have the capability to do the necessary programming of the co-ordinates or trace the mold. Scientific-Atlanta has a Bendix-Cordax inspection machine in use here in Atlanta. They are being contacted to determine how feasable tracing the mold will be.

Due to previous commitments to other programs, I have not had the freedom to spend as much time on this project as had been planned. It is foreseeable that the completion date of this program might overrun the anticipated date of 11 December 1973. I will keep you informed of any further development in this area.

As always, please do not hesitate to call if you should have any questions.

Very truly yours,

Henry P. Cotten
Project Director

Project A-1543

A-1543

ENGINEERING EXPERIMENT STATION

GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

9 October 1973

Dr. W. E. Swinson, Jr.
2178-B Briarcliff Village Shopping Center
Atlanta, Georgia 30345

Reference: Dental Inlay Study

Subject: Progress Letter No. 4 for the period 11 September 1973 to 10 October 1973.

Dear Dr. Swinson:

As reported to you earlier, a sample mold and dental burrs were sent to Mr. Rod Stallard at Bendix, Automation and Measurements Division, Dayton, Ohio. On 9 October, he called with some of his conclusions. He stated that because of the very irregular surface of the mold, the use of this type of measuring equipment would be very difficult. It would be hard to achieve either the accuracy or the repeatability required. He is going to summarize his findings in a letter that will be mailed to me sometime this week.

I have been investigating the use of small pantograph engraving machines. These are simple to operate, but they do require skill by the operator to achieve good results. Certain models that I have studied have some drawbacks. However, they are low-priced (about $1,700.00) when compared to other systems we have seen.

Last month, we prepared the proposal for the color comparison study. The time spent in preparing the proposal along with some inital investigating was charged to this project. Mr. Albert McSweeney spent 20% of his time while Dr. J. E. Rhodes, Jr. spent 10%. The paperwork is being processed and you should be receiving a copy soon.

As always, if you should have any questions, please do not hesitate to call.

Very truly yours,

Henry P. Cotten
Project Director

dab
Project No. A-1543

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

14 November 1973

Dr. W. E. Swinson, Jr.
2178-B Briarcliff Village Shopping Center
Atlanta, Georgia 30345

Reference: Dental Inlay Study

Subject: Progress Letter No. 5 for the period of 11 October 1973 to 10 November 1973.

Dear Dr. Swinson:

A test duplicate of the mold from the human tooth is being machined at McCann Machine, Inc. in Athens, Georgia. To demonstrate the method and to speed the machining time, aluminum is being used for the duplicate. This method uses a hydraulic 3-D tracer attached to a conventional milling machine. The machining will take approximately three weeks. This will include initial set-up and any down-time problems that might arise.

Since the duplicate will not be ready until the 1st week in December, this will not allow me enough time to do an adequate evaluation for the Final Report to you. I would like to extend the present deadline of 10 December 1973 to 10 January 1974. This would be a no-cost extension. The possibility of having to extend this deadline was pointed out in Progress Letter #3 on 10 September 1973.

As always, if you should have any questions, please do not hesitate to call.

Very truly yours,

Henry P. Cotten
Project Director

dab
Project A-1543

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

13 December 1973

Dr. W. E. Swinson, Jr.
2178-B Briarcliff Village Shopping Center
Atlanta, Georgia 30345

Reference: Dental Inlay Study

Subject: Progress Letter No. 6 for the period of 11 November 1973 to 10 December 1973

Dear Dr. Swinson:

Machining of the duplicate inlay at McCann Machine was completed on 26 November. Test and evaluation of the machine techniques as well as the fit of the inlay to the tooth is currently being done.

A meeting with you was arranged on 29 November to discuss the duplicate. Certain places where a radius corner occurred prevented the duplicate from seating as well as the original. However, key areas such as the feather edges and perimeter edges were accurately reproduced. Termination of the project was discussed. It was decided to finish the present effort and complete the Final Report for delivery in January.

I will keep you informed as to the completion of the report. As always, if you should have any questions, please do not hesitate to call.

Very truly yours,

Henry P. Cotten
Project Director

dab

Project A-1543

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

11 January 1974

Dr. W. E. Swinson, Jr.
2178-B Briarcliff Village Shopping Center
Atlanta, Georgia 30345

Subject: Final Report on "Dental Inlay Study"

Dear Dr. Swinson:

The purpose of this letter is to summarize results performed on the subject contract.

A. Background

In April 1973, Dr. W. E. Swinson, Jr., came to the Sensor Systems Division of the Engineering Experiment Station (EES) at Georgia Tech seeking assistance in determining the feasibility of machining dental inlays rather than casting them. After the discussion, a formal proposal (EES Proposal ST-SSD-73-032) was prepared, in which Sensor Systems Division offered to investigate the literature, procedures for duplicating or measuring cavities, new materials for making impressions, use of three-dimensional measuring machines, and use of three-dimensional numerically controlled milling machines. This report summarizes the work done by EES under the resulting contract.

In the production of dental inlays, the most common procedure involves making an impression of the cavity, producing a wax pattern of the inlay, and then casting a gold inlay. These procedures follow the usual investment casting techniques. This approach has the disadvantage that it is slow and that much of the work must be done in a dental laboratory remote from the dentist's office. Approximately half the inlays made by this casting process usually require further machining by the dentist

before the inlay will fit the cavity. Some have variations of 0.010 inch or more compared to the cavity. These variations are due to changes in humidity and temperature which cause the mold or wax to either shrink or swell. Any rough handling of the pieces during or after casting will also affect the accuracy of the cast inlay.

In considering the proposed approach, it is realized that any attempt to directly measure the cavity within a patient's mouth would create numerous errors. The measuring device would have to be fixed to the patient's mouth in such a way as to eliminate any motion between the two. As an alternative to direct measurement, a mold of the cavity would be made. This mold would then be either scanned by a coordinate measuring machine to produce a tape for a numerical control machine or traced by a hydraulic or electronic tracing, milling machine to produce a machined inlay.

B. Literature Search

A literature search was made to determine what machines are commercially available that would either provide direct control by tracing an object or produce a paper tape to be used on numerically controlled equipment.

1. Measuring & N/C Machines

This search located two companies who manufacture 3-axis measuring machines that produce a paper-tape output: Cincinnati Milacron, of Cincinnati, Ohio, and Bendix, Automation & Measurement Division, of Dayton, Ohio. If these could be used, a highly accurate, 3-axis numerically controlled milling machine made by Boston Digital Corporation, of Ashland, Massachusetts, would be considered as the best N/C tape machine to produce an inlay.

Both Cincinnati Milacron and Bendix were contacted to discuss the possibility of tracing a mold of a cavity to produce a paper tape. These

machines are primarily used as inspection machines to check known dimensions from drawings. Although some models have the capability of generating tape, for the present application, the small size and irregularity in the surface of the mold would cause problems in tracing the surface. The operator must know when and where (with reference to three dimensions) the probe is touching the mold. A minicomputer is integrated in the system to pick off coordinates at prearranged points; i.e. every 0.001 inch, for example. Any extraneous movement by the operator is recorded, along with all other points from the mold. In automatic scanners, without an operator, the machine is not able to resolve indecisions, such as a vertical obstruction. When one is encountered, the machine does not know whether to go up or down. Even obstructions with a slope produce resolution errors as the angle of the slope increases toward 90 degrees.

An estimate of the number of points to define an inlay was made. Assuming a cube one-quarter inch square, taking points every 0.001 inch around the perimeter would take 250,000 points. To produce these points on paper tape, would require 2,083 feet of tape, whereas most rolls of N/C tape are 1,000 feet long.

Another tracing technique in this same area of dental restorations has been proposed by F. W. Paul of Carnegie-Mellon University, Pittsburgh, Pa. In ASME Paper 73-DET-48, he describes the use of multiple-index holography with subsequent computer processing of the holographic image to drive a manufacturing process, such as a N/C machine. This process does eliminate the human error of the mechanical scanners. However, the equipment to do this type of laser scanning is not commercially available. Substantial cost for development would be needed just to prove the idea.

2. Tracers

Several manufacturers produce tracing machines which will machine an object while tracing a master. This has the advantage that any movement of the stylus against the master moves the cutter. Any area of the master can be retraced any number of times.

Tracers can be divided into two categories, hydraulic and electronic. A hydraulic tracer uses a three-way proportional valve on the stylus and hydraulic cylinders to move the work table. An electronic tracer uses linear variable differential tranformers or similar devices to move servomotors that drive the table. When contouring in two directions, an electric tracer can hold tolerances of $\pm$0.0005 inch. For three-dimensional work, tolerances can be within $\pm$0.001 inch. Most other tracers work to two-dimensional tolerances of $\pm$0.003 inch and three-dimensional tolerances of $\pm$0.005 inch.

As in coordinate-measuring machines, there are both manual and automatic tracers. Here again, the same problems that applied to automatic scanners apply to tracers. Certain areas create indecision as to the motion of the machine. With manual tracers, the operator must be careful not to exert excess pressure on the stylus which would bend the stylus or the mold, causing the machine to cut too much from the material.

3. Pantograph

The final type of machine considered as able to machine an inlay from a mold is a pantograph. This is a four-bar linkage that has the adjustment to provide for either increasing or reducing the size of an original model. The pantograph is entirely hand operated. Spindle speeds up to 20,000 rpm are available. As with tracers, the accuracy of operation of the device depends on the skill of the operator. The pantograph is considerably smaller in size and simpler than a tracer, and hence does not cost as much as the other types of tracing equipment. A drawback to the use of a 3-D pantograph is that a full-size, 1:1 copy cannot be made. Gorton Machine Corporation of Racine, Wisconsin, and H. P. Preis Engraving Machine Company of Hillside, New Jersey, are two manufacturers of these machines.

C. Mold of Tooth Cavity

By using a product known as Adaptic, manufactured by Johnson and Johnson, a mold was made of a human tooth cavity. This molding material

is usually used as an anterior/posterior dental restorative. It is a two-part resin-bonded quartz composite. With a working time of 1½ minutes and a set-up time of 5 minutes, this material is particularly well suited for molding the cavity. Shrinkage of the Adaptic is less than 0.5%. A suitable release agent, such as cocoa butter, must be used to separate the mold from the cavity. A steel pin was inserted into the mold before it hardened to allow handling of the mold during machining.

D. Machining of the Inlay

Suitable equipment to test the feasibility of machining an inlay from the mold was sought. A hydraulic, Bridgeport milling machine with a three-dimensional tracer was located at McCann Machinery in Athens, Georgia. The machined inlay was to be aluminum since it is somewhat softer and easier to machine than stainless.

The cavity mold and a rod of aluminum were mounted on a round, machined bar. By using V-blocks on the machine's bed, the holding fixture could be rotated to provide access to all sides of the mold. A 1/16-inch diameter, ball-end, end mill was used to machine the aluminum. Total machining time to produce the copy of the mold was seven hours. Set up time to machine the fixture, etc., was another four hours.

E. Evaluation of Machining Techniques

The machined inlay did not fit the cavity as well as did the mold, due in part to the use of the ball-end mill. There were several square corners on the mold that ended up with a radius on the machined part. Critical areas along the perimeter of the inlay were faithfully reproduced. These "feather edges" are what actually determines the fit to the cavity. The top and inner surfaces are not as critical as these can be machined by the dentist to fit.

As mentioned earlier, excess pressure on the tracing stylus can cause problems in trying to trace a mold. With the mold supported on the small

metal rod in its base, the pressure of the stylus would move the mold. This would cause a small amount of additional material to be machined. Here again, the accuracy of the machined part depends on the skill of the operator.

Stainless steel is approximately three times tougher than aluminum to machine, and depth of cut also cannot be as much as with aluminum. It is estimated that to machine the same inlay from stainless steel would take 21 hours or more for the first one. With experience, it is thought that the machining time would drop to five or six hours for stainless steel.

F. Conclusions

It is concluded that the machining of an inlay is feasible. However, there are certain difficulties to the implementation of this process.

1. Measuring and N/C Machines

The approach using a measuring machine and numerical control appears to have enough problems that to implement the idea in practical hardware would be prohibitive. A standardized set of inlays could be made, each form having definite mathematical boundaries so that every point on the perimeter would be known. By programming these on paper tape, identical inlays could be made. The dentist would then fit the tooth to the inlay. There is a drawback to this plan. Over 4,000 different inlay models would be needed.

2. Tracing Machines

This type of machine seems to be best suited to do the inlay machining. Machines of this type usually are somewhat large and heavy to reduce deflection and error. Spindle speeds are somewhat low (5,000 rpm) for the small sized cutters that are used. However, the technology and equipment are readily available. The techniques for cutting the inlay need improvement. By using other types of cutters, a machined inlay could be produced to have a better fit than the one actually machined. A single type of cutter could be used effectively if the original cavity contours were ground to eliminate sharp corners, etc.

3. Pantographs

While these will move in three directions, most three-dimensional pantographs will not reproduce a one-to-one copy. These are strictly enlarging or reducing machines. The more accurate machines are almost as large and heavy as the tracers. To produce a one-to-one copy, special machinery would have to be built. This would require development costs, new tooling, etc.

G. Recommendations

As with a study of this type, there are many degrees of success. We believe that we have completed the objectives that were set forth. Further work in this field should be considered to resolve some of the difficulties that were encountered. For this or any other matter, we would be anxious to serve you. This could range from an advisory capacity to further development of the idea. We concur that a meeting is necessary to discuss this report and to consider the possibilities of future work.

By terminating the project at this date, we believe that we have reached a desirable decision point. The budgeted estimate to determine the feasibility was $9,951. To date, approximately $7,500 has been expended within the budget.

Very truly yours,

Henry P. Cotten
Project Director

dab

Project No. A-1543